# PROBABILISTIC STRUCTURAL ANALYSIS METHODS FOR SPACE TRANSPORTATION PROPULSION SYSTEMS

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## PROBABILISTIC STRUCTURAL ANALYSIS

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# PRESENTATION OUTLINE

- ISSUES
- STATE-OF-THE-ART
- NEEDS IDENTIFIED
- PROPOSED PROGRAM
- SUMMARY

## ISSUES

***CERTIFICATION OF SPACE TRANSPORTATION PROPULSION SYSTEMS:***

* IS COSTLY.

* IS TIME CONSUMING.

* IS DIFFICULT DUE TO UNCERTAINTIES IN ACTUAL OPERATING CONDITIONS.

* NEEDS TO BE REPEATED FOR:

  - *MODIFICATIONS TO EXISTING SYSTEMS.*
  - *UPDATED CHANGES IN OPERATING CONDITIONS.*

# CERTIFICATION: STATE-OF-THE-ART

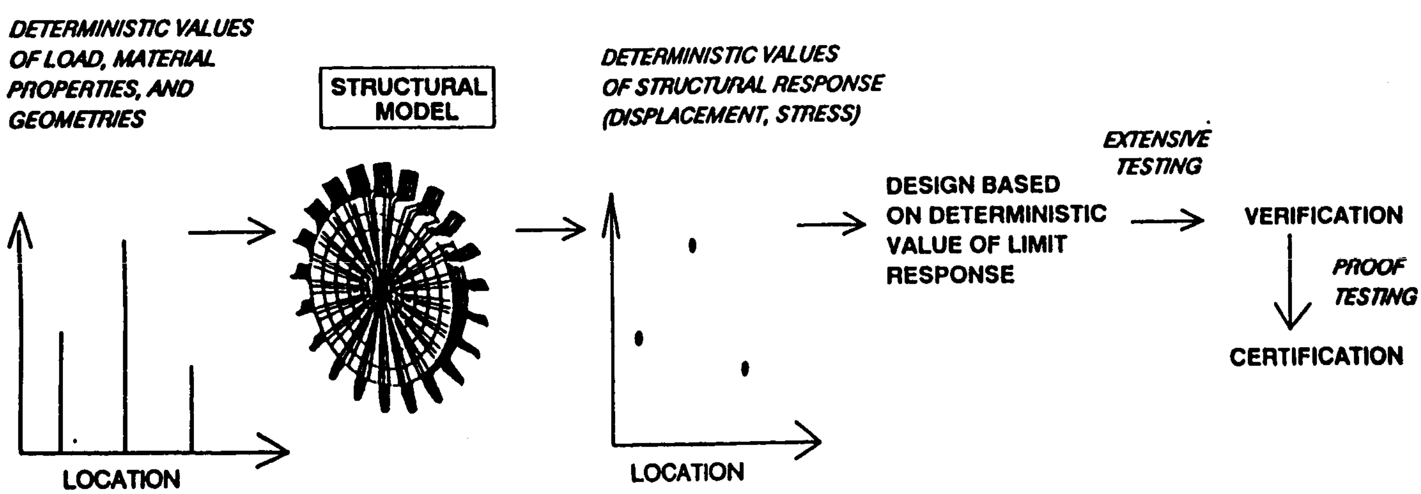
* ***CERTIFICATION OF PROPULSION SYSTEMS IS DONE ON THE BASIS OF:***
  - MEETING LIMIT LOAD CONDITIONS.
  - AVAILABILITY OF TECHNOLOGY BASE THAT CAN BE SAFELY EXTRAPOLATED WITHIN THE LIMITS.

* ***THE RELIANCE IS ON***
  - DETERMINISTIC STRUCTURAL RESPONSE.
  - EXTENSIVE TESTING FOR VERIFICATION.
  - PROOF TESTING FOR CERTIFICATION.

* ***THE CERTIFICATION METHODOLOGY PROVIDES LITTLE GUIDANCE FOR HEALTH MONITORING.***

# DETERMINISTIC CERTIFICATION METHODS: STATE-OF-THE-ART

***CURRENT DESIGNS ARE BASED ON DETERMINISTIC STRUCTURAL ANALYSIS WITH TEST-INTENSTIVE VERIFICATION AND PROOF TESTING FOR CERTIFICATION.***

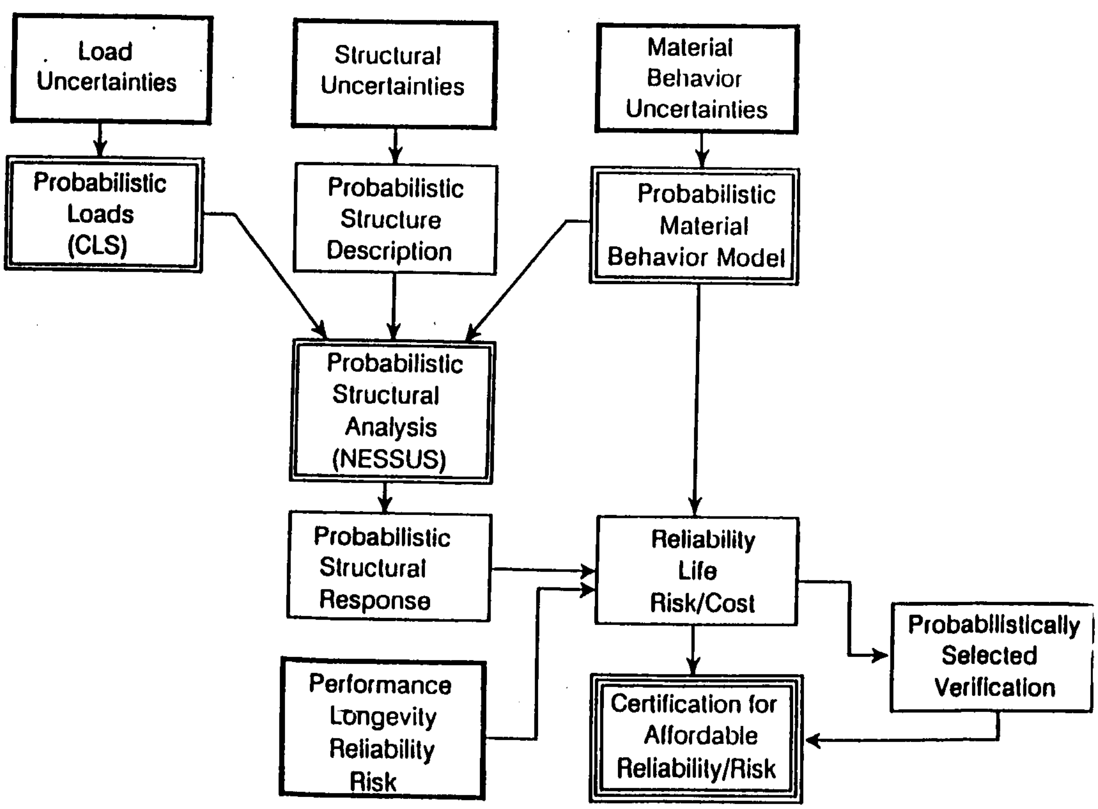


*PROBABILISTIC SIMULATION IS <u>THE</u> RATIONAL ALTERNATIVE IN THE ABSENCE OF TRADITIONAL TECHNOLOGY BASE FOR ADVANCED VEHICLE SYSTEMS WHICH ARE DRIVEN BY:*

- *High Risk*
- *Quantum Performance Improvements*
- *Short Schedules*
- *Limited Resources*

## PROBABILISTIC STRUCTURAL ANALYSIS METHODS

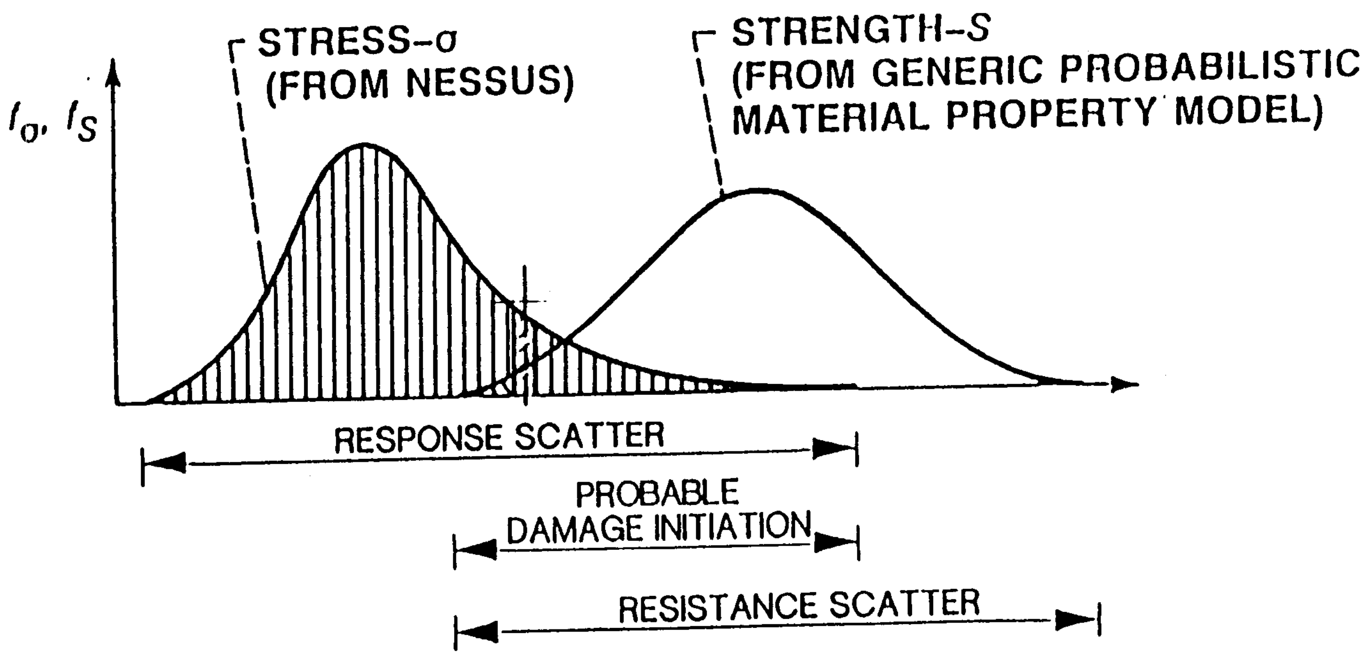
**ON-GOING PROGRAMS AT NASA LEWIS RESEARCH CENTER**



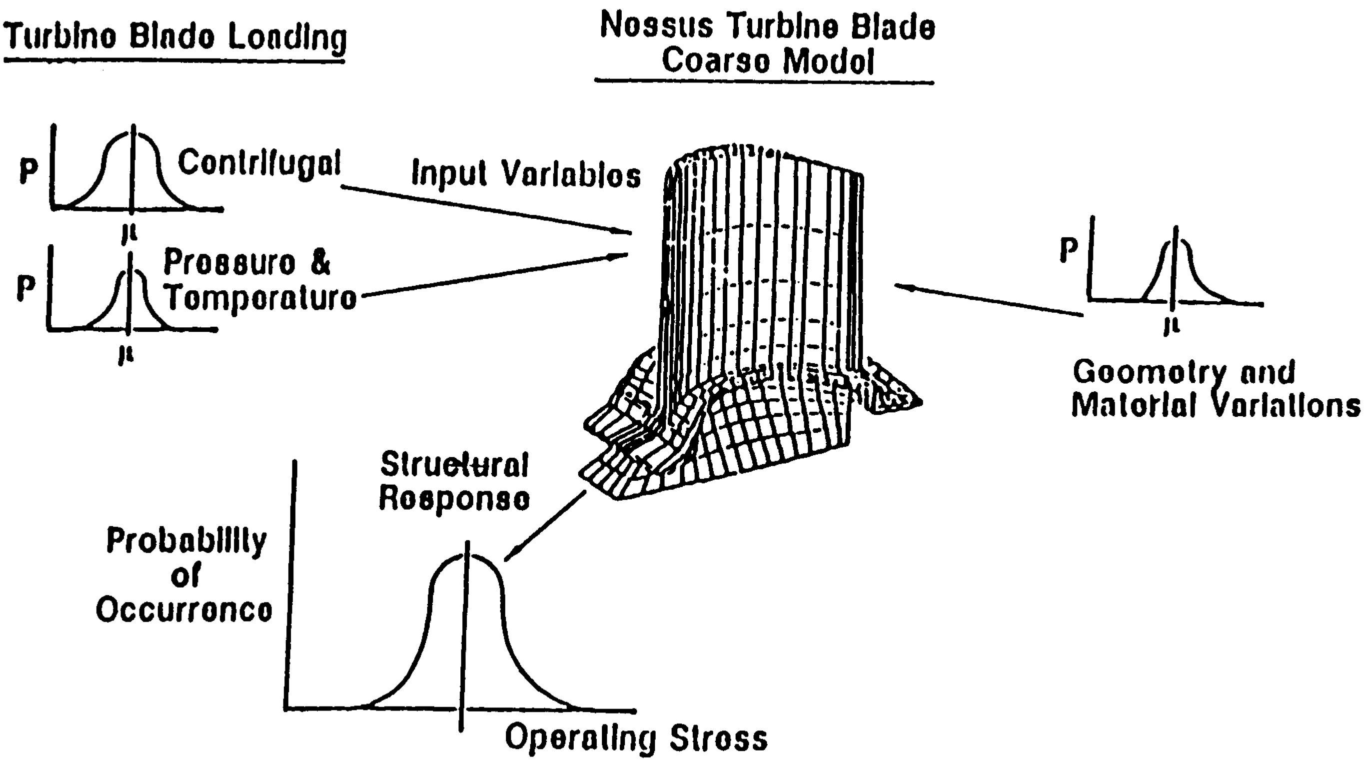
# PROBABILITY OF FAILURE - DAMAGE INITIATION

$$\underbrace{P_f}_{\text{PROBABILITY OF FAILURE}} = P\,(\underbrace{\sigma}_{\text{STRESS}} \geq \underbrace{S}_{\text{STRENGTH}})$$

$$P_f = \int_{-\infty}^{\infty} \left( \int_{-\infty}^{x} f_S(s)\, ds \right) f_\sigma(x)\, dx$$



# Component Response Analysis Using CLS Coupled With PSAM




LeRC Contracts

CLS - Composite Loads Spectra
PSAM - Probabilistic Structural Analysis Methods - SWRI

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# Random Variables Considered and Their Statistics

| No. | Random Variable | Type | Affected FEM Quantities | Mean | Standard Deviation |
|---|---|---|---|---|---|
| 1 | Material axis Z | Material | Anisotropic | -0.087266 radian | 0.087644 |
| 2 | Material axis Y | orientation | material | -0.034907 | 0.087644 |
| 3 | Material axis X | Effects | Orientation angles | -0.052360 | 0.087644 |
| 4 | Elastic modulus | Material | Elastic constants | 18.38E6 psi | 0.4595E6 |
| 5 | Poisson's ratio | properties | | 0.386 | 0.00965 |
| 6 | Shear modulus | | | 18.63E6 psi | 0.046875E6 |
| 7 | Geometric lean | Geometrical | Node coordinates | 0 deg | 0.14 deg |
| 8 | Geometric tilt | variations | | 0 deg | 0.14 deg |
| 9 | Geometric twist | | | 0 deg | 0.30 deg |
| 10 | Mixture ratio | System | Pressure, temperature, | 0.0 | 0.02 |
| 11 | Fuel inlet pressure | independent | centrifugal force | 30.0 psi | 5.00 |
| 12 | Oxidizer inlet pressure | loads | | 100.00 psi | 26.00 |
| 13 | Fuel inlet temperature | | | 37 °R | 0.60 |
| 14 | Oxidizer inlet temperature | | | - 164 °R | 1.33 |
| 15 | Pump efficiency | Component | Pressure, temperature, | 1.00 | 0.008 |
| 16 | Head coefficient | independent loads | centrifugal force | 1.024 | 0.008 |
| 17 | Coolant seal leakage | Local effects | Temperature | 1.0 | 0.10 |
| 18 | Hot gas seal leakage | | | 1.0 | 0.05 |

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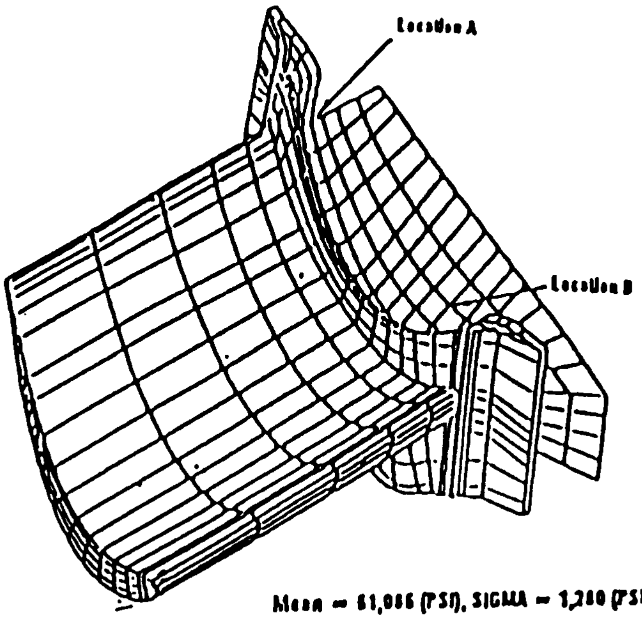
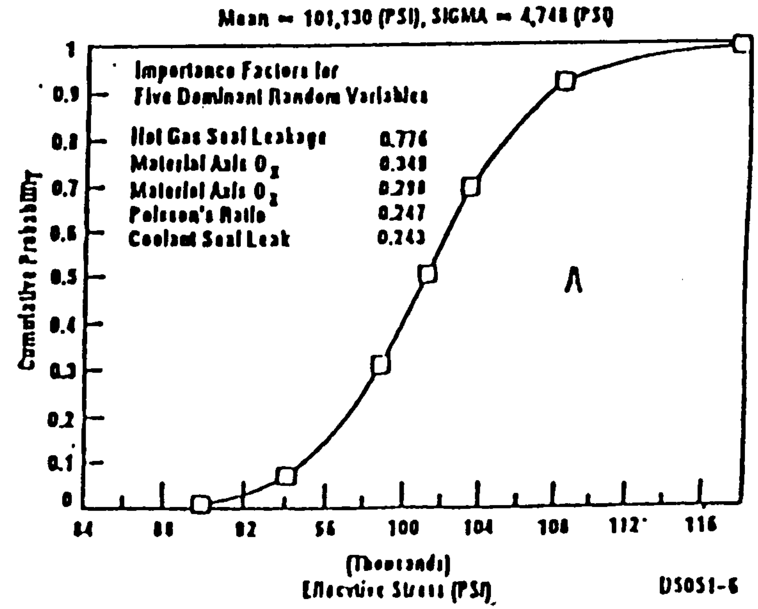
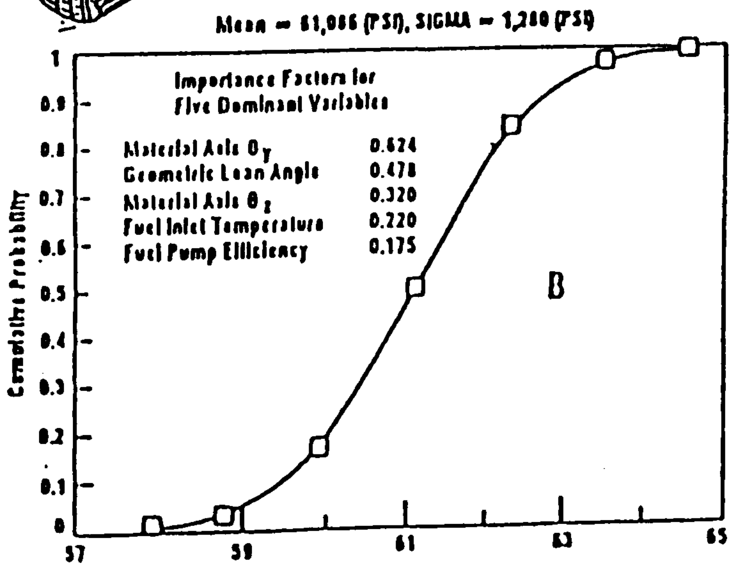
STRUCTURES DIVISION
Structural Mechanics Branch

NASA
Lewis Research Center

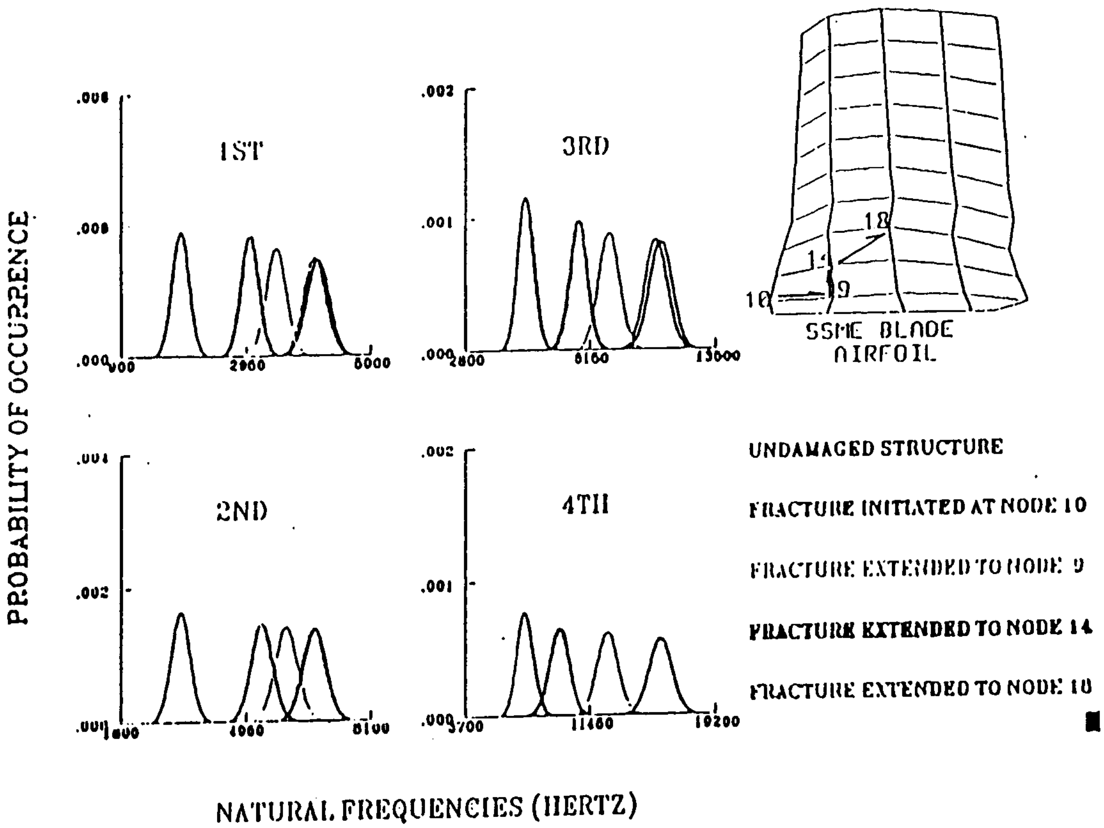


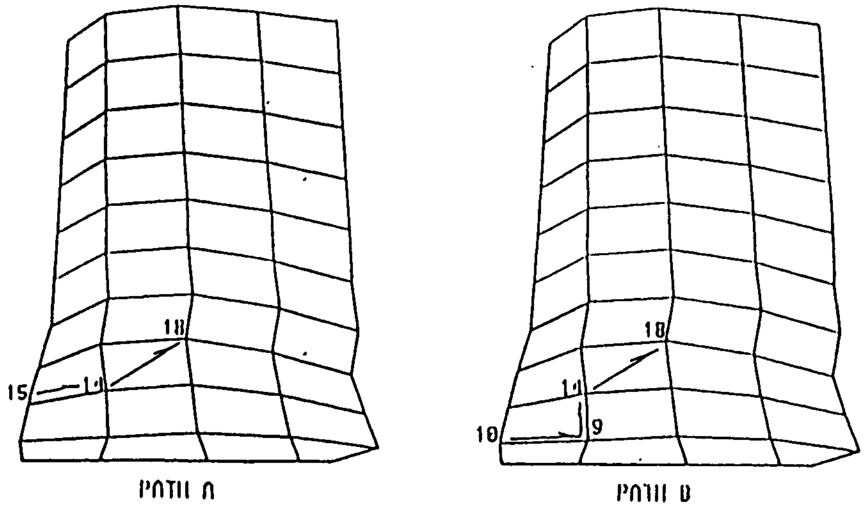




# TYPICAL STRESS RESPONSE FOR 2nd STAGE BLADE

# NATURAL FREQUENCIES DECREASES AS FRACTURE PROGRESSES



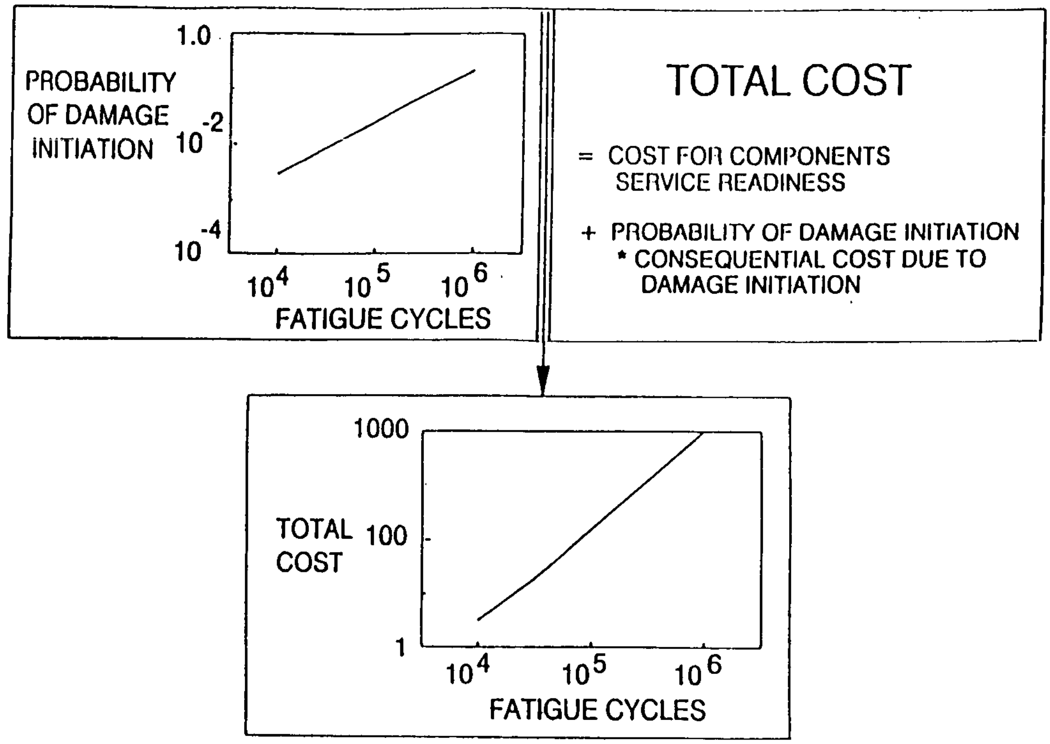

# PROBABILITY OF COMPONENT DAMAGE PROPAGATION PATH CAUSED BY 100,000 FATIGUE CYCLES



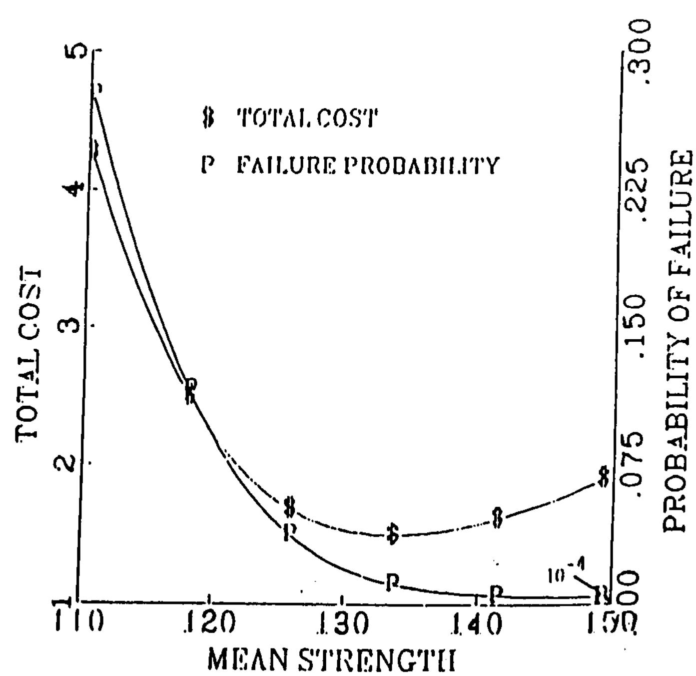

PROBABILITY OF
PATH A OCCURS
= 0.00001

PROBABILITY OF
PATH B OCCURS
= 0.0002

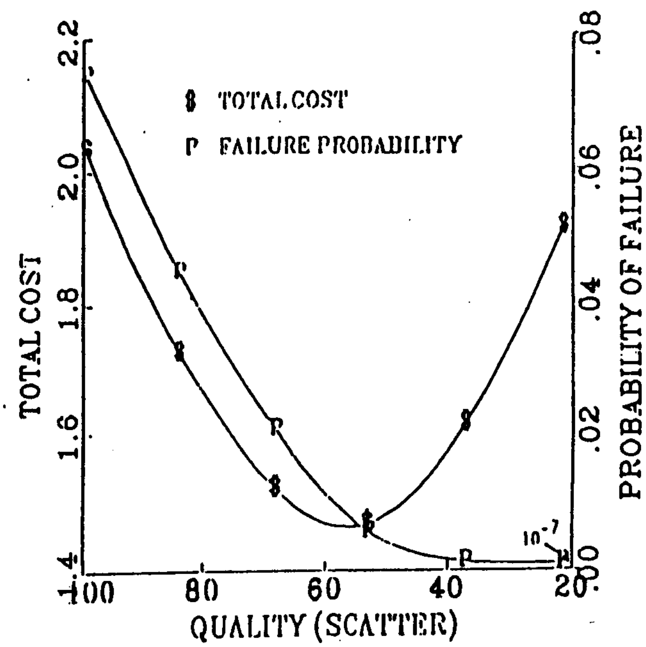
# PROBABILISTIC RISK-COST ASSESSMENT




THE TOTAL COST TO IMPROVE THE STRUCTURAL RELIABILITY CAN BE QUANTIFIED IN TERMS OF MEAN STRENGTH (GIVEN QUALITY)



THE TOTAL COST TO IMPROVE THE STRUCTURAL RELIABILITY CAN BE QUANTIFIED IN TERMS OF QUALITY CONTROL (GIVEN MEAN STRENGTH)




STRUCTURES DIVISION

NASA
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SSME STRUCTURAL DURABILITY

*PROBABILISTIC STRUCTURAL ANALYSIS METHODS DEVELOPMENT*

*FY90 Add component risk assessment capability*
- *State-of-the-art method*
- *Incorporate uncertainties in a multifactor interaction equation for material strength degradation*
- *Probabilistic nonlinear constitutive relationships*

*FY91 Add system risk assessment capability*
- *Fault tree concepts*
- *Global model concepts*

*FY92 Develop qualification/certification capability*
- *Incorporate structural fracture concepts*
- *Probabilistic progressive fracture*
- *Probabilistic life/durability*

*FY93 Develop system health monitoring criteria*
- *Inspection criteria/intervals*
- *Updated life*
- *Retirement for cause*

# NEEDS IDENTIFIED

***FOR MULTI-LEVEL PROBABILISTICALLY SIMULATED CERTIFICATION OF PROPULSION SYSTEMS***

* COMPUTATIONAL METHODS NEED TO BE DEVELOPED FOR CONDUCTING PROBABILISTIC ANALYSES AT VARIOUS LEVELS OF THE SYSTEM ( SUB-COMPONENT, COMPONENT, SYSTEM ).
* SMART DECISION-ORIENTED CODES NEED TO BE DEVELOPED FOR AUTOMATED, FAST, AND EFFICIENT PROBABILISTIC ANALYSIS AT ALL LEVELS OF THE SYSTEM.
* AUTOMATED SELF-ADAPTIVE CODES NEED TO BE DEVELOPED FOR PERFORMING GLOBAL/ LOCAL NONLINEAR ANALYSES.
* A GLOBAL/LOCAL DAMAGE INITIATION LIBRARY IS NEEDED WITH CAPABILITY FOR AUTOMATIC IDENTIFICATION OF APPLICABLE DAMAGE INITIATION MECHANISMS.
* COMPUTATIONAL METHODOLOGIES NEED TO BE DEVELOPED FOR PROBABILISTIC ASSESSMENT OF PROGRESSIVE DAMAGE GROWTH AND GLOBAL/LOCAL DAMAGE COALESCING.
* RISK MODELS NEED TO BE DEVELOPED FOR PROBABILISTICALLY QUANTIFYING RELIABILITY, RISK, AND COST.
* SIMULATION METHODS ARE NEEDED FOR DEVELOPING DATA/RESULTS REQUIRED FOR SYSTEM VERIFICATION.
* PROBABILISTIC METHODS NEED TO DEVELOPED FOR DETERMINING CRITERIA AND SELECTING MINIMUM NUMBER OF TESTS REQUIRED FOR SYSTEM VERIFICATION.
* METHODOLOGIES ARE NEEDED FOR SYSTEM VERIFICATION USING EXISTING/NEW TECHNIQUES/EQUIPMENT.
* QUANTIFIABLE CERTIFICATION CRITERIA MUST BE DEVELOPED. PROBABILISTIC SIMULATION WILL ACCOMPLISH THIS GOAL.
* MATHODOLOGIES NEED TO BE DEVELOPED FOR HEALTH MONITORING BASED ON PROBABILISTICALLY QUANTIFIED RELIABILITY AND RISK.

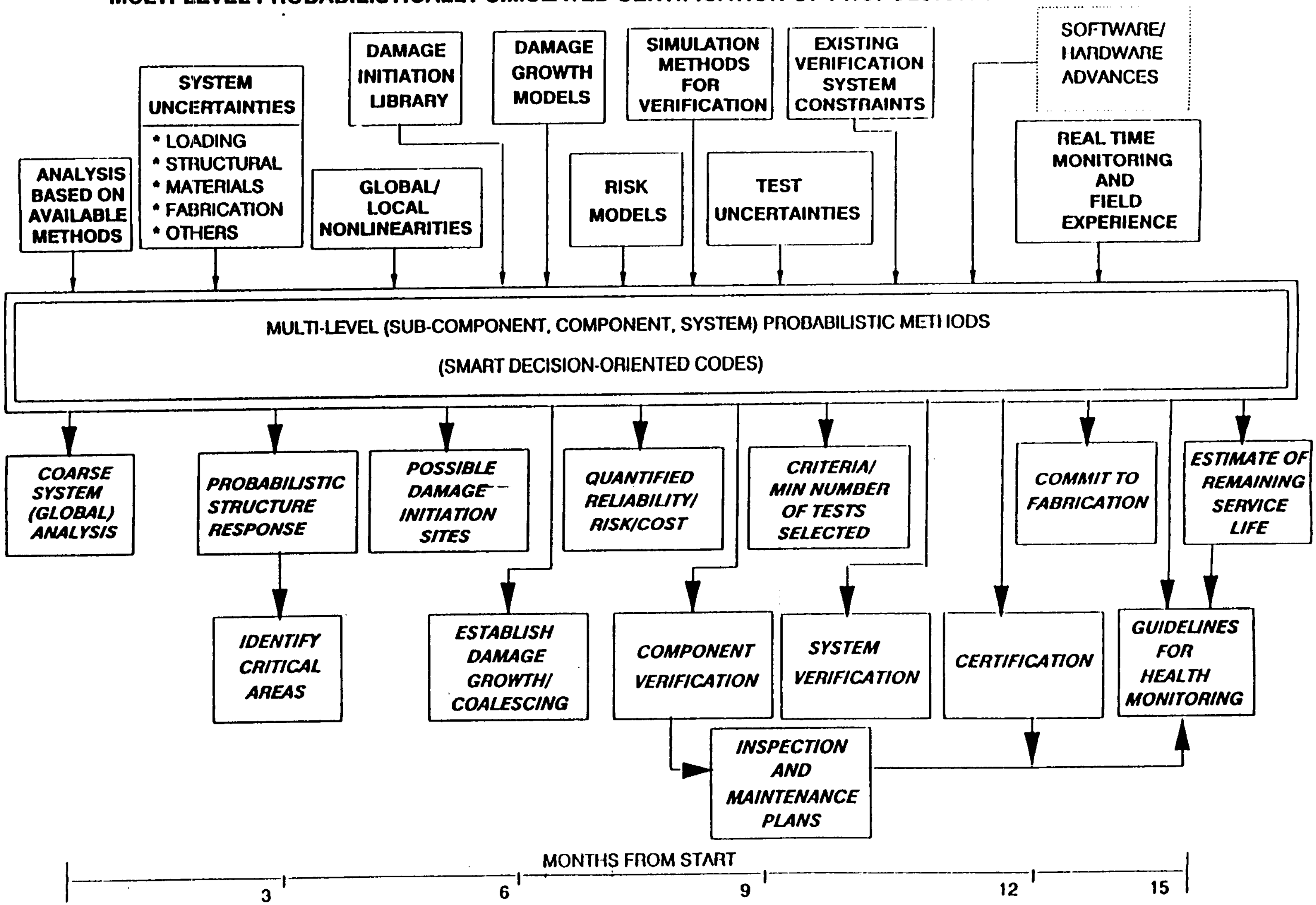
# PROPOSED PROGRAM

***MAJOR OBJECTIVE:***

SOFTWARE SYSTEM TO PROBABILISTICALLY SIMULATE CERTIFICATION OF SPACE TRANSPORTATION PROPULSION STRUCTURAL SYSTEMS.

## PROPOSED PROGRAM: BLOCK DIAGRAM

## MULTI-LEVEL PROBABILISTICALLY SIMULATED CERTIFICATION OF PROPULSION SYSTEMS



# PROPOSED PROGRAM

## MULTI-LEVEL PROBABILISTICALLY SIMULATED CERTIFICATION OF PROPULSION SYSTEMS

**OBJECTIVE:** Automated software packages for multi-level system probabilistic structural integrity, progressive damage and risk analyses required for testing, verification, certification and guidance for health monitoring of propulsion systems.

**JUSTIFICATION:** Propulsion systems are presently certified based on deterministic structural analysis, local failure models, a large experimental database, and gradually increasing confidence based on qualitative judgement and continually increasing in-flight experience. This results in certification of designs which do not account for realistic load, material characteristics and responses. Such a practice is very expensive and inefficient. An economically attractive alternate based on modelling for actual operating conditions is by probabilistic analysis.

**APPROACH:** Research will be conducted to develop efficient, automated, cost-effective probabilistic structural analysis methods. The research activities will consist of (1) telescopic analysis capability for analyzing propulsion systems at various structural detail levels, automatically with a minimum number of system parameters, (2) smart solver codes for efficient solutions with automated identification of minimum number of degrees of freedom required to capture the physics of the system, (3) automated nonlinear global/local structural analysis with user-independent decision making for solution of nonlinearities and damage-critical areas, (4) damage initiation library for identifying material/structure/load-specific damage sites/types, (5) damage growth and pattern for predicting site and type of failure, (6) risk models for predicting cost/reliability/insurance, (7) simulation methods for generating data/results required for verification, (8) criteria and test selection for identification of suitable minimum experiments, (9) verification using existing systems, (10) certification based on quantifiable reliability and risk levels, and (11) guidance for health monitoring based on probabilistically quantified risk.

**RESOURCES:** $25M over a 5-year period (See attached time schedule chart)

## PROPOSED PROGRAM: TIME SCHEDULE AND RESOURCES

MULTI-LEVEL PROBABILISTICALLY SIMULATED CERTIFICATION OF PROPULSION SYSTEMS

| RESEARCH ACTIVITY | YEARS FROM START ($ M) | | | | | TOTALS PER ACTIVITY ($ M) | TARGET GOALS |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | | |
| *1. TELESCOPIC ANALYSIS CAPABILITY* | 0.5 | 1 | 0.5 | | | *2* | MIN HUMAN INTERACTION |
| *2. SMART SOLVERS* | 0.3 | 0.7 | 0.8 | 0.2 | | *2* | MIN TURNAROUND TIME |
| *3. AUTOMATED NONLINEAR GLOBAL/LOCAL ANALYSIS* | | 0.8 | 0.8 | 0.4 | | *2* | USER-TRANSPARENT COMPLETE ANALYSIS |
| *4. DAMAGE INITITATION LIBRARY* | 0.2 | 0.8 | 0.7 | 0.3 | | *2* | AUTOMATED FAILURE MODE INDENTIFICATION |
| *5. DAMAGE GROWTH AND PATTERN* | | 0.5 | 1 | 0.5 | | *2* | DEVELOPMENT OF INSPECTION AND MAINTAINENCE PLANS |
| *6. RISK MODELS* | | 0.5 | 1.5 | 1 | | *3* | MORE RELIABLE ESTIMATE OF REMAINING SERVICE LIFE |
| *7. SIMULATION METHODS FOR VERIFICATION* | | | | 1.5 | 0.5 | *2* | COMPONENT VERIFICATION |
| *8. CRITERIA & SELECTION OF TESTS* | | | 0.8 | 0.9 | 0.3 | *2* | CRITERIA AND MIN NUMBER OF TESTS |
| *9. VERFICATION USING EXISTING SYSTEMS* | | | | 1 | 2 | *3* | DEMONSTRATION OF METHODS/RESULTS |
| *10. CERTIFICATION METHODOLOGIES* | | | | 1 | 2 | *3* | CERTIFICATION |
| *11. HEALTH MONITORING* | | | | | 2 | *2* | GUIDANCE FOR HEALTH MONITORING |
| TOTALS PER YEAR ($ M) | *1* | *4.3* | *6.1* | *6.8* | *6.8* | *25* | |

# PROGRAM IMPLEMENTATION

* MULTI-INSTITUTION PARTICIPANT DEVELOPMENT. (DIFFERENT INSTITUTIONS DEVELOP DIFFERENT PARTS.)
* ANNUAL RELEASES WITH PROGRESSIVE SOPHISTICATION CAPABILITY.
* WORKSHOPS FOR NEW CAPABILITY USER INSTRUCTIONS.
* EARLY-ON ADAPTATION INTO PRELIMINARY AND FINAL DESIGN ENVIRONMENTS.
* VERIFICATION/COMPARISON WITH PAST DESIGN AND FIELD EXPERIENCE AT USERS FACILITY.
* FORMATION OF PARTICIPANTS' USERS GROUP.
* FORMATION OF SOFTWARE MAINTENANCE INSTITUTION.

# SUMMARY

*CERTIFICATION OF SPACE TRANSPORTATION PROPULSION SYSTEMS:*

* ISSUES:
  - COST/TIME/ACTUAL OPERATING CONDITIONS.

* STATE-OF-THE-ART
  - CERTIFICATION/DETERMINISTIC METHODS/PROBABILISTIC STRUCTURAL ANALYSIS METHODS.

* NEEDS IDENTIFIED
  - PROBABILISTIC METHODS FOR UNCERTAINTIES IN LOADING/STRUCTURE/MATERIAL/DAMAGE/FABRICATION.
  - PROBABILISTIC RISK MODELS/TEST SELECTION/VERIFICATION/CERTIFICATION.
  - GUIDANCE FOR HEALTH MONITORING.

# SUMMARY (CONTINUED)

* **PROPOSED PROGRAM**

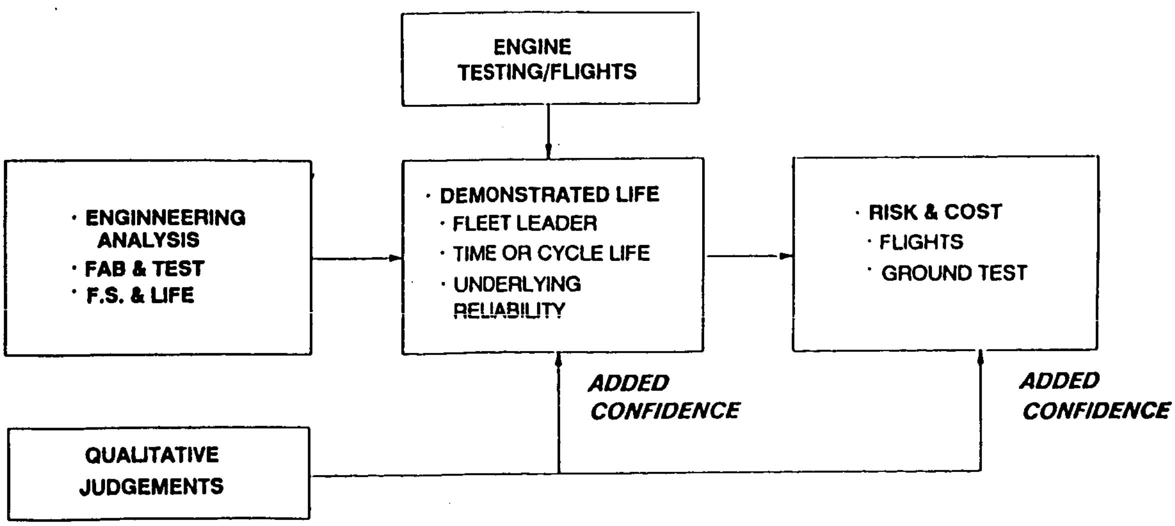
  - OBJECTIVE: PROBABILISTICALLY SIMULATED CERTIFICATION.
  - JUSTIFICATION: ACTUAL OPERATING CONDITIONS/QUANTIFIABLE RISK/ DECISION-ORIENTED SMART CODES/LESS COST/ GUIDANCE FOR HEALTH MONITORING.
  - APPROACH: 11 RESEARCH ACTIVITIES.
  - TIME SCHEDULE AND RESOURCES: $25M OVER A 5-YEAR PERIOD.

* **IMPLEMENTATION**

  - INCORPORATION INTO A DESIGN ENVIRONMENT.
  - EDUCATION TO USERS.
  - VERIFICATION/COMPARISON WITH PAST DESIGN AND FIELD EXPERIENCE.

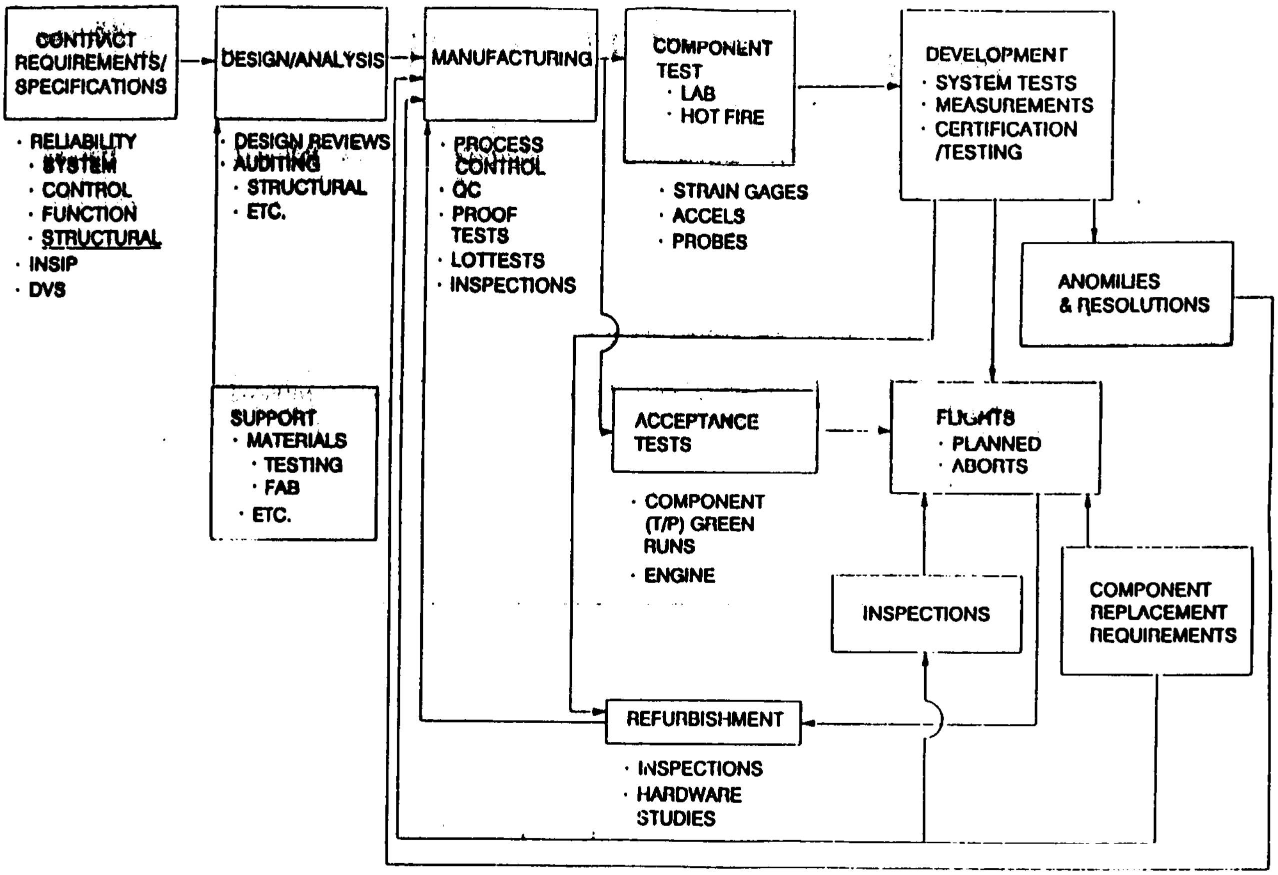
LIQUID ROCKET PROPULSION

CURRENT DETERMINISTIC APPROACH



## LIQUID ROCKET PROPULSION
## CURRENT CERTIFICATION PROCESS

GOAL: QUANTIFIED DECISION PROCESS FOR RISK & COST BASED ON TOTAL PROCESS




# PROPOSED PROGRAM

**MULTI-LEVEL PROBABILISTICALLY SIMULATED CERTIFICATION OF PROPULSION SYSTEMS**

**OBJECTIVE:** AUTOMATED SOFTWARE PACKAGES FOR INTEGRATED SYSTEM LIFE CYCLE MULTI-LEVEL PROBABILISTIC STRUCTURAL INTEGRITY, PROGRESSIVE DAMAGE AND RISK ANALYSES REQUIRED FOR CERTIFICATION AND HEALTH MONITPRING OF PROPULSION SYSTEMS.

**JUSTIFICATION:**
- DESIGN FOR REALISTIC IN-FLIGHT ENVIRONMENT
- QUANTIFIABLE RELIABILITY/RISK/COST
- DECISION-ORIENTED SMART CODES
- LESS COST
- GUIDANCE FOR HEALTH MONITORING

## PROPOSED PROGRAM (CONTINUED)

**MULTI-LEVEL PROBABILISTICALLY SIMULATED CERTIFICATION OF PROPULSION SYSTEMS**

**APPROACH:**

- TELESCOPIC ANALYSIS CAPABILITY
- SMART SOLVER CODES
- AUTOMATED NONLINEAR GLOBAL/LOCAL STRUCTURAL ANALYSIS
- DAMAGE INITIATION LIBRARY
- DAMAGE GROWTH AND PATTERN
- RISK MODELS
- SIMULATION METHODS FOR VERIFICATION
- CRITERIA AND TEST SELECTION
- VERIFICATION USING EXISTING SYSTEMS
- CERTIFICATION
- HEALTH MONITORING

**RESOURCES:** $25M OVER A 5-YEAR PERIOD

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# PROBABILISTIC STRUCTURAL ANALYSIS METHODS FOR SPACE TRANSPORTATION PROPULSION SYSTEMS

ISSUES: ***CERTIFICATION OF SPACE TRANSPORTATION PROPULSION SYSTEMS:***

* IS COSTLY AND TIME CONSUMING.
* IS DIFFICULT DUE TO UNCERTAINTIES IN ACTUAL OPERATING CONDITIONS.
* NEEDS TO BE REPEATED FOR MODIFICATIONS TO EXISTING SYSTEMS AND FOR ENHANCED CAPABILITY IN OPERATING CONDITIONS.

## PROPOSED ACTIONS/PROGRAM:

* CONTINUATION/AUGMENTATION OF ON-GOING NASA PROGRAMS.
* MULTI-LEVEL SELF-ADAPTIVE SOFTWARE FOR GLOBAL/LOCAL NONLINEAR ANALYSIS.
* LIBRARY OF POSSIBLE FAILURE MODES.
* DECISION LOGIC FOR DAMAGE INITIATION/COALESCING/GROWTH.
* RISK MODELS/PROBABILISTICALLY SELECTED TESTING/VERIFICATION/CERTIFICATION.
* GUIDELINES FOR HEALTH MONITORING.

## MAJOR OBJECTIVE:

* **MULTI-LEVEL PROBABILISTICALLY SIMULATED CERTIFICATION FOR SPACE TRANSPORTATION PROPULSION STRUCTURAL SYSTEMS.**

## MAJOR MILESTONES:

* MULTI-LEVEL PROBABILISTIC STRUCTURAL ANALYSIS METHODS.
* LIBRARY OF POSSIBLE FAILURE MODES.
* LOGIC FOR DAMAGE INITIATION/COALESCING/GROWTH.
* SOFTWARE FOR COMPONENT/SYSTEM TESING/VERIFICATION/CERTIFICATION.
* STREAMLINED SOFTWARE FOR IN-SERVICE HEALTH MONITORING.
* SOFTWARE VALIDATION.